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Acoustics of the Cristal Baschet

F. Gautier (1), J-L. Le Carrou (2), A. Elmaian (1), F. Bousquet (3)

(1) LAUM, CNRS, Université du Maine, Le Mans, France
(2) LAM-IJLRA, CNRS, UPMC-Univ. Paris 06, Paris, France
(3) Structures Sonores EURL, Le Tomple, Quezac, France

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ABSTRACT

The Cristal Baschet is a musical instrument which was developed by Bernard and Francois Baschet in 1952. Its sound is produced by friction-induced vibrations, resulting from the sliding contact between the musician's finger and a glass rod. Today, the Cristal Baschet is an instrument which can cover up to five octaves and has reached a maturity that makes it a key instrument in contemporary music. This instrument is composed of four major subsystems: glass rods (also called glass bows), metal rods (called vibrating rods), a metallic support plate (called collector) and large thin panels (called sound diffusers). The aim of the paper is to provide further understanding of the acoustic functioning of the Cristal Baschet for manufacturing and musical interests.
Experimental study of the instrument shows that the friction of the wet fingers of the musician on the glass rods creates vibrations which are transmitted to the collector and are then radiated through sound diffusers. Fingers' motions show a succession of adhesion and slip phases on the rod. Such behavior is known as the stick-slip phenomenon similar to bow movements observed in violin playing. When playing, a key point is to control this stick-slip phenomenon. Drawing on similar studies on the violin and cello, we suggest here an adaptation of the Schelleng diagram which enables us to qualify the compromise between the force applied to the rod and the finger's velocity, which are two fundamental control parameters during this stick-slip phase. The contact surface between the finger and the glass bow, and the contact conditions (presence of fat or acid on the skin, roughness, the use of multiple fingers) are other control parameters of the instrument. Despite their relevance, these parameters are not addressed in the study presented here. The proposed diagram allows us to define ranges of the control parameters which corresponds to a playable tune.

THE CRISTAL BASCHET AND ITS CREATORS

Invention of the "*Structures Sonores*"

In the fifties, Francois and Bernard Baschet created a new family of musical instruments, that they called "*Structures sonores*" [1]. During more than half a century, their work as instruments' makers was a huge empirical research based on the readings of textbooks in acoustics. Following one of the experiments reported by H. Bouasse [2], they experienced the acoustics of friction of glass rods, like those used in chemical laboratories since the 18th century. They used this element to develop the Cristal, which became a major instrument for contemporary music. In 1998, Bernard and François Baschet met a collaborator, Frédéric Bousquet, who contributed to develop the Cristal, by extending its tessitura to reach 5 octaves. Their instruments, considered as "sound sculptures" were played all over the world (see Figure 1) and exposed in art galleries and major museums. All the instruments created by the Baschet brothers are acoustical instruments and are using human made materials: polymers, composite fibbers, light alloys, titanium. They developed their own approach of music and a specific musical pedagogy adapted to the sound produced by their instruments [3].

The "Cristal" in 2010

The Cristal is a keyboard instrument able to play up to 5 octaves (see Figure 2). It is composed of a large number of glass rods, also called glass bows, connected to the metal rods, called vibrating rods and attached to a metallic support plate, called the collector. For radiating the sound, large thin panels of complex shapes, called sound diffusers are connected to the collector.

Figure 1: "*Structures sonores*" used by the musical group Lasry Baschet

The musician, also called cristalist, plays by wetting his fingers with water and by rubbing them on the glass rods in order to produce friction-induced vibrations.

The acoustics of friction involves complex physics and is found in many musical or not musical situations [4]. The aim of the paper is to provide a clear understanding of the instrument's acoustic functioning, in terms of making and musical use.

ANALYSIS OF THE ACOUSTIC FUNCTIONING OF THE CRISTAL BASCHET

Identification of the acoustical functions

By examining the functioning of the Cristal Baschet, four main acoustical systems can be identified (as shown in Figure 3):

1. The excitation mechanism whose role is to generate sound: this is achieved by the finger/glass rod interaction which leads to a complex vibratory instability.
2. The resonator whose role is to fix the playing frequency:

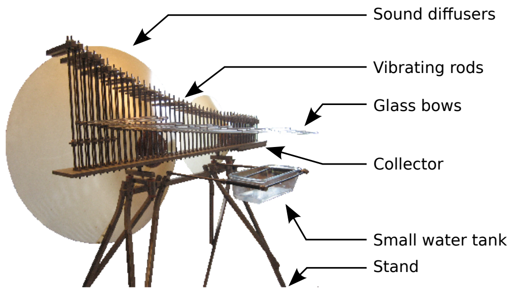

Figure 2: Description of a three and a half octaves Cristal Baschet

the glass rod connected to two vibrating rods and one mass which can be tuned in order to produce all the tones of the musical scale.

3. The collector whose role is to transmit the vibrations from the resonator to the diffuser. Its shape and thickness are variable and complex in order to limit the transmission of vibrations between the different glass rods.
4. The diffusers whose role is to radiate the sound. They can be made with metallic sheets of complex shape, more or less conical or by polymer cones. Several diffusers of different sizes can be connected to the collector.

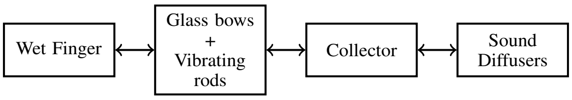

Figure 3: Block diagram presenting the parts of the Cristal and their acoustical function

Experimental investigation of the Cristal Baschet

A Cristal is tested and two experimental investigations are developed to understand and characterize the excitation mechanism.

Experimental modal analysis of the resonator

An experimental modal analysis is performed on a resonator at the middle of the instrument's compass. This is carried out by impact testing: an impact force is applied at the basis of the vibrating rods while velocity is measured by using a laser vibrometer. A set of transfer functions is computed by the LMS software Teslab, leading to the identification of flexural mode shapes, eigenfrequencies and modal damping coefficients. The mode shape of the main flexural mode involved in playing conditions, is shown in Figure 4. This mode shape was confirmed by a numerical prediction using a classical Finite Element Method (RDM6.0 software, developed at Université du Maine, Le Mans). Unfortunately, since many unknown prestresses inside the different rods are present and important, a precise numerical prediction of the eigenfrequencies of the assembly is hard to obtain.

It was also shown that when playing, the mode given in Figure 4 is dominant. Consequently, when playing, the glass rod has a translational rigid body motion. No longitudinal waves are observed in the glass rods as we expected.

Experimental study of the finger/rod interaction

In order to analyze in detail the finger/rod interaction, a specific experimental set-up is carried out. A wet finger rubs the glass rod connected to two vibrating rods attached on the collector. A zoom of this scene is filmed using a high-speed camera. The camera's frame rate is set at 4091 frames per second for a 1024×256 pixels image size which allows an accurate image of the finger/rod displacements. A typical frame obtained with this experimental set-up is shown in Figure 6. In order to precisely

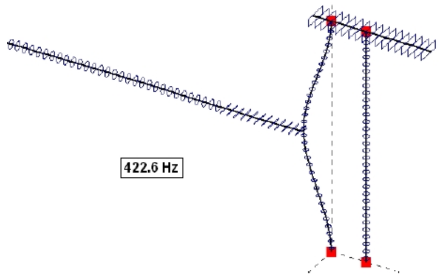

Figure 4: Modal shape of the main flexural mode of the resonator involved when playing the Cristal Baschet

measure the relative motion between the fingertip and the rod, two markers are installed, as shown in Figure 5, and tracked by an edge detection algorithm.

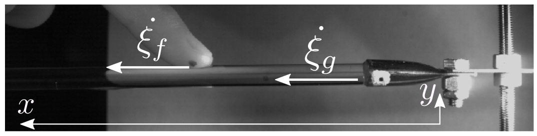

Figure 5: Typical frame obtained by the high speed camera

In Figure 6, relative velocity between the finger and the rod versus time is shown. This relative velocity is found to alternate between two values. These two values are either 0 (the finger sticks to the rod) or $0.3m/s$ (the finger slips on the rod). This motion can be linked to that of the bowed string [5, 6].

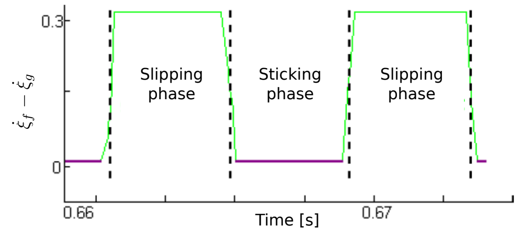

Figure 6: Relative velocity [m/s] between the finger and the glass bow versus time

CONDITIONS FOR SOUND GENERATION

Basic model of the finger/glass bow interaction

As a first approximation, we propose to represent the finger/glass bow interaction by a single degree of freedom model, shown in Figure 7-a. The glass bow is assimilated to a mass m, in contact with the finger (conveyor belt in the model) moving along the horizontal axis with uniform velocity V. The connection between the glass bow and the vibrating rod is realized by a spring of stiffness k and a dashpot c. A normal force N is applied at the top of the mass, simulating the pressure exerted by the finger of the player on the glass bow.

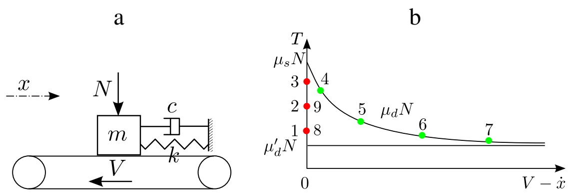

Figure 7: a) Single degree of freedom model and b) associated friction law

The equation of motion describing this model is:

$$m\ddot{x} + c\dot{x} + kx = T, \quad (1)$$

where T is the tangential force due to the friction between the wet finger and the glass bow. Supposing that the friction coefficient depends on the relative velocity, as shown in figure 7-b. Two different situations can be observed, according to the velocity $\dot{x}$:

$$\begin{cases} \text{Sticking phase:} & \dot{x} = V,\ |T| \leq \mu_s N \\ \text{Slipping phase:} & \dot{x} \leq V,\ T = \mu N \text{ with } \mu = \frac{\mu_d'(V-\dot{x})+\mu_s v_h}{V-\dot{x}+v_h} \end{cases} \quad (2)$$

This model allows to highlight the stick-slip phenomenon occurring when playing the Cristal Baschet. The plot of the phase diagram (Figure 8) shows the notion of limit cycle, where sticking and slipping phases are periodically repeated. The sticking phase corresponds to the interval in which the glass bow sticks to the finger and therefore takes the speed of the finger (Figure 7 and Figure 9 steps 1, 2, 3, 8 and 9). The slipping phase corresponds to the interval in which the glass bow moves in opposite direction to that of the finger (Figure 7 and Figure 9 steps 4, 5, 6 and 7). Figure 8 shows the influence of the normal force N on the nature of the limit cycle and its influence on the transient time required to achieve this periodic motion.

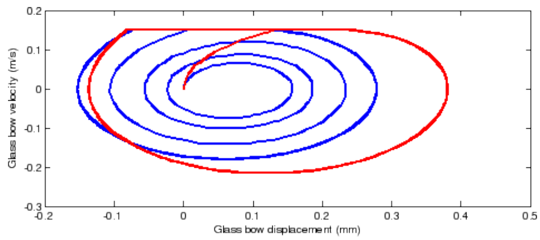

Figure 8: Limit cycles depending on finger force and velocity (blue: $N = 10N$, $V = 0.15m/s$ / red: $N = 20N$, $V = 0.15m/s$)

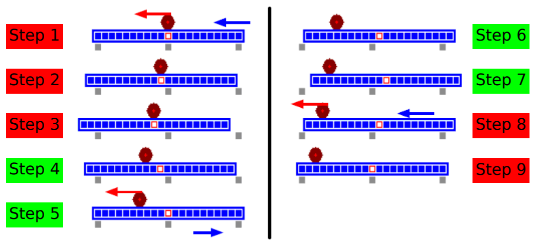

Figure 9: Stick-slip phenomenon occurring between the finger and the glass bow. Each of these steps are positioned on the friction law curve in Figure 7-b

We can see from the limit cycles in Figure 8 that the periodic motion is reached more or less quickly according to the finger's force and its velocity. For the smaller value, the sticking phase is reached after the fourth slipping period (blue curves). A quicker transient is observed for a higher finger force (red curves) as the periodic motion starts almost immediately. This notion of transient time is directly linked to the quality of the note attack.

Presentation of the Schelleng's diagram

In 1973, J.C Schelleng established a diagram identifying the main kinds of motion of a bowed string of a violin [5]. Among them, he identified the Helmholtz motion regime, which represents the regular motion in a classical performance. He explained that normal playing conditions coincide with conditions for obtaining the Helmholtz motion and identified ranges of control parameters which lead to the Helmholtz motion. Out of these ranges, the sound is traditionally not considered musically acceptable. Given a bow position and velocity, lower forces produce a "surface sound", while higher forces produce aperiodic "raucousness".

Application of the Schelleng's diagram to the Cristal Baschet

We propose to adapt the Schelleng's diagram to the case of the Cristal. Such a diagram is useful to define the ranges of control parameters which lead to "normal" sound. In the case of the Cristal, three kinds of control parameters are used: the finger force N normally applied on the glass rod, the finger velocity V, the contact conditions (surface of skin involved in the contact, condition of lubrication). We choose to investigate the influence of N and V, considering the contact conditions as being given. This investigation is an adaptation of studies developed for the violin [5, 6, 7].

When the glass bow moves from the equilibrium position, a force due to the stiffness of the vibrating rod is exerted on it, as both are connected. This force can be expressed as $F_{rod} = kx$, where k and x are the stiffness of the vibrating rod and the displacement of the connecting point between the glass bow and the vibrating rod. In order to trigger at least a slip in a nominal period τ, this force must exceeds $(\mu_s - \mu_d)F$, where F is the force exerted by the finger on the glass bow. A theoretical maximum value for finger force N is deduced:

$$F_{max} = \frac{\pi v \sqrt{km}}{2(\mu_s - \mu_d)} \quad (3)$$

It is also important to determine a theoretical minimum value for the finger force N. The force exerted by the glass bow on the vibrating rod includes a dissipative term $F_0 = c\dot{x}(0,t)$, where c is the damping coefficient previously introduced and $\dot{x}(0,t)$ the velocity at the connecting point between the vibrating rod and the glass bow at time t. The power dissipated by the vibrating rod over a period can be derived with the assumption that both sliding and sticking phases last a half of the period τ as explained previously:

$$\langle V \rangle = \frac{1}{\tau}\int_{-\tau/2}^{\tau/2} F_0(t)\dot{x}(0,t)dt = cV^2 \quad (4)$$

Furthermore, the maximal power P_{sup} that the finger can give to the glass bow over a period can be expressed using the static friction limitation $\mu_s N$ imposed during sticking phase:

$$P_{sup} = \frac{1}{\tau}\int_{\tau} F(t)\dot{x}(\beta L, t)dt = \frac{V}{2}(\mu_s - \mu_d)N \quad (5)$$

The finger can provide the power dissipated by the vibrating rod if P_{sup} exceeds P, so we can deduce the expression of the minimum force:

$$F_{min} = \frac{2cV}{\mu_s - \mu_d} \quad (6)$$

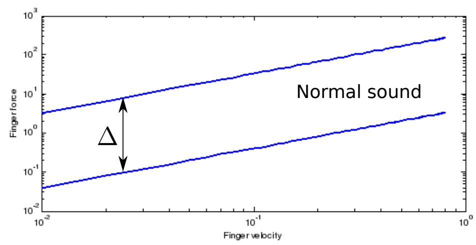

Figure 10: Schelleng's diagram applied to Cristal Baschet

Figure 10 is a Schelleng's diagram for the Cristal. It is obtained using the F_{max} and F_{min} expressions and highlights the region of playability, where a good compromise between force and velocity prevents the player from producing an abnormal sound.

The size of the band Δ corresponding to the "normal" sound area is given by

$$\Delta = \log\left(F_{max}/F_{min}\right) = \log\left(\pi\frac{\sqrt{mk}}{4c}\right). \qquad (7)$$

Δ increases if the glass rod mass increases or if the vibrating rod stiffness increases or if the resonator's damping decreases.

CONCLUSION

The sound produced by the Cristal Baschet is a friction-induced sound. An experimental study of the interaction between the finger and the glass bow has been achieved using a high-speed camera. Stick-slip phenomenon has been simulated and interpreted thanks to a simple one degree of freedom model. This model allows us to adapt the Schelleng's diagram previously developed for the violin.

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